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Overcome electrical, thermal problems in high-power op amps

A 1-chip power op amp is capable of driving ±35V at ±10A. This article, part 1 of a 2-part series, describes the electrical and thermal problems accompanying the use of such high-power devices and gives advice on how to solve the problems. Part 2 will present a variety of applications for the op amp.

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By understanding the practical problems associated with the use of a high-power operational amplifier, you can avoid such circuit problems as oscillation and distortion. Further, a study of the amplifier's thermal-protection characteristics allows you to make actual measurements of heat-sink design margins. The 150W LM12 is capable of supplying ±35V at ±10A; its peak-power rating of 800W makes the device capable of driving reactive loads. To obtain optimum performance from the amplifier, you should observe proper procedures for grounding, bypassing, loading, and providing efficient heat-sinking to the device.

Power op amps are subject to many of the same problems that general-purpose op amps experience. Excessive input or feedback resistance can cause a dc offset voltage on the output because of bias-current drops, or it can combine with stray capacitance to cause oscillations. Improper supply bypassing and capacitive loading, alone or in combination, can also result in oscillations. In many cases, you can avoid spending hours tracking down seemingly incomprehensible design problems by monitoring the op amp's output with a wideband oscilloscope.

For instance, when the LM12 op amp drives low-impedance loads and provides current transients greater than 10A, the effects of inductance and resistance of wire interconnects can become troublesome. Furthermore, in order to make the IC dissipate 90W continuously, you must mount it to an adequate heat sink.

The management and protection circuitry of the LM12 can also affect the system's operation. For example, if the total supply voltage exceeds ratings or drops below 15V, the op amp will shut off completely. Case temperatures above 150°C also cause complete shutdown until the temperature drops to 145°C. Reactivation of the op amp could take several seconds, depending on the heat-sink design. When the LM12's dynamic safe-area protection is activated, the main feedback loop loses control and output drive current is reduced. Oscillations may also result. In ac applications, the dynamic protection will cause waveform distortion.

To avoid spurious oscillation, you should bypass the op amp's supply terminals with low-inductance capaci-

Power-amplifier circuitry demands that you use special care in grounding and bypassing and that you protect the amplifier from the effects of reactive loads.

tors that have short leads and are located close to the package terminals. High-power op amps require larger bypass capacitors than do low-power units. The LM12 will be stable as long as you use good-quality electrolytic bypass capacitors whose values are greater than 20 μF. The current in the supply leads is a rectified component of the load current. Unless you provide adequate bypassing, this distorted signal can feed back into the op amp's internal circuitry. To obtain low distortion at high frequencies, you must bypass the supplies with capacitors of 470 μF or more at the package terminals.

With ordinary op amps, lead-inductance problems usually occur in inadequately bypassed supply leads. Power op amps are also sensitive to inductance in the output lead, particularly in the presence of heavy capacitive loading. To minimize common inductance with the load, you should connect feedback to the input directly from the output terminal. Make sure that when you use remote sensing, you provide a high-frequency feedback path directly from the output terminal.

Lead inductance can also cause voltage surges on the supplies. If the op amp has long leads to its power source, energy stored in the lead inductance when the output is short-circuited can get dumped back into the supply bypass capacitors upon removal of the short circuit. You can reduce the magnitude of this transient by increasing the size of the bypass capacitor near the IC. With 20-μF local bypass capacitors, these voltage surges are important only if the lead length exceeds a couple of feet (ie, when lead inductance is greater than 1 μH). Twisting together the supply and ground leads minimizes the transient effect.

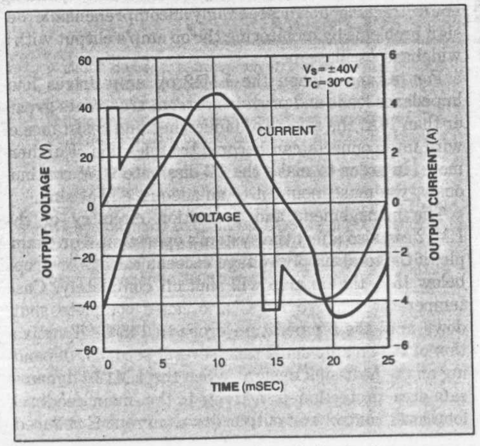

***Fig 1—Output voltage can exceed supply levels** when an op amp drives an inductive load. These curves show the activation of the LM12's dynamic safe-area protection. The stored energy in the inductor drives the output voltage beyond the supply levels.*

Avoid ground loops

In fast, high-current circuitry, various problems can arise from improper grounding. In general, you can avoid difficulties by returning all grounds separately to a common point. When such a connection is impractical, be sure to minimize the ground-path impedance for the supply bypasses, the load, and the input signal. To provide optimum grounding, use ground planes whenever possible.

Many problems unrelated to system performance are traceable to the grounding of line-operated test equipment that's used for system checkout. When you're using several pieces of test equipment, hidden paths are particularly difficult to sort out, but you can minimize the problem by using current probes or isolated oscilloscope preamplifiers. Eliminating any direct ground connection between the signal generator and the oscilloscope's synchronization input solves ground-feedback problems.

When a push-pull amplifier goes into power limit while driving an inductive load, the energy stored in the inductance can drive the output to voltages beyond the supply levels. **Fig 1**, for example, shows the overload response of an LM12 that's driving ±36V at 40 Hz into a 4Ω load in series with 24 mH.

The IC has internal supply-clamp diodes, but these clamps have a parasitic current that dissipates roughly half the clamp current across the total supply voltage. The internal protection circuitry can't control this dissipation; if the dissipation is sustained, the IC will experience catastrophic failure. You should, therefore, use external diodes to clamp the output to the power supplies.

Further, if you don't use external clamp diodes, a short circuit between the output and the supplies can induce random failures. Therefore, it's prudent to use output clamp diodes even when the load isn't obviously inductive. Failure of the IC is particularly violent when it's operating from low-impedance supplies: The V^+ pin can vaporize and blow a hole through the top of the can. If the LM12 fails, install diodes before you try again.

Because the clamp diodes clamp only current transients, they usually don't need heat sinking. When transients reach 15A, however, forward drop can reduce the efficacy of the clamp diodes. If the forward drop exceeds 0.8V, the clamp to the negative supply can lose some of its effectiveness. To reduce the diode's forward drop, mount this diode to the op amp's heat sink. A third diode (D_3 in **Fig 2**) will protect the amplifier in the unlikely case that D_2's forward drop becomes excessive. For D_3 you must use a diode that's capable of dissipating a continuous power level that's

A look at the LM12

The performance of the LM12 puts the op amp in a class with discrete and hybrid power amplifiers. The IC incorporates internal management circuitry that provides smooth turn-on and automatic protection against a variety of fault conditions; it offers instantaneous limiting of the power transistors' peak junction temperatures.

Table 1 summarizes the LM12's performance. The op amp's input common-mode range extends to within 1V of the positive supply and to 3V above the negative supply. If the applied signal exceeds the input-voltage range, no input-polarity reversal occurs. If the signal drives the inputs beyond the supply voltages, no damage results.

TABLE 1—TYPICAL CHARACTERISTICS OF THE LM12

PARAMETER	CONDITIONS	VALUE
INPUT OFFSET VOLTAGE	$V_{CM} = 0$	2 mV
INPUT BIAS CURRENT	$V_{CM} = 0$	150 nA
VOLTAGE GAIN	$R_L = 4\Omega$	50V/mV
OUTPUT-VOLTAGE SWING	$I_{OUT} = \pm 1.5A$ $\pm 10A$	±38V ±35V
PEAK OUTPUT CURRENT	$V_{OUT} = 0$	±13A
CONTINUOUS DC DISSIPATION	$T_C = 25°C$ $100°C$	90W 55W
PULSE DISSIPATION	$T_{ON} = 10$ mSEC 1 mSEC 0.2 mSEC	120W 240W 600W
POWER OUTPUT	$R_L = 4\Omega$	150W
TOTAL HARMONIC DISTORTION	$R_L = 4\Omega$	0.01%
BANDWIDTH	$A_V = 1$	700 kHz
SLEW RATE	$R_L = 4\Omega$	9V/μSEC
SUPPLY CURRENT	$I_{OUT} = 0$	60 mA

The IC offers compensation for unity-gain feedback, and small-signal bandwidth is 700 kHz. The part's slew rate is 9V/μsec, even when the LM12 is connected as a follower. This slew rate translates to a 60-kHz power bandwidth under load with a ±35V output swing. The op amp is stable with or without capacitive loading; the maximum load capacitance depends upon loop gain. The IC exhibits no spurious output stage oscillations and requires no series-RC snubber on the output.

The LM12 delivers ±10A output current at any output voltage, yet is completely protected against output overloads, including short circuits to the supplies. Peak-temperature limiting within the power-transistor array provides dynamic safe-area protection. On-chip circuitry controls the IC's turn-on characteristics by keeping the output open-circuited until the total supply voltage reaches 15V. The output also becomes open-circuited when the case temperature exceeds 150°C or as the supply voltage approaches the BV_{CEO} of the output transistors. The op amp withstands overvoltages as high as 100V.

The LM12's guaranteed power ratings are not established by statistical methods from sample tests. Instead, the manufacturer interpolates the ratings from actual measurements of power capability into thermal limit; these measurements are standard production tests for the op amp.

The LM12 is supplied in a steel TO-3 package with four through leads; the case is the V^- connection. A gold-eutectic die-attach and a molybdenum interface let the op amp avoid thermal-fatigue problems under power-cycling conditions. Two voltage grades (60 or 80V total supply span) are available; both are specified for either the military or industrial temperature range.

The thermal and protection circuitry in a power op amp is crucial to the part's survival in situations that produce excessive junction-temperature rise.

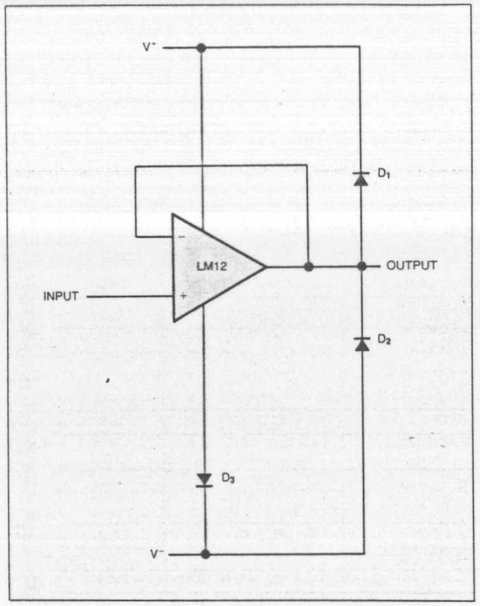

Fig 2—Output clamp diodes D_1 and D_2 dump inductive-load current *into the supplies when the op amp goes into power-limit mode. You might need to use the third diode, D_3, if D_2's forward drop is excessive.*

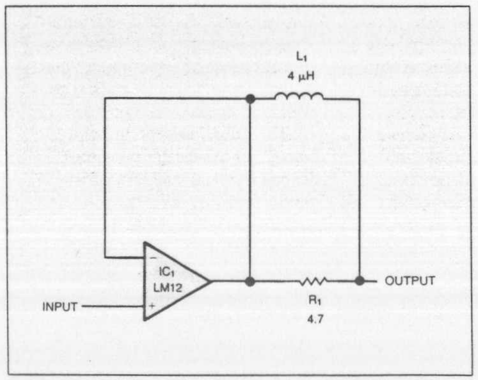

Fig 3—Use an inductor to isolate capacitive loads. *The noninductive resistor prevents resonance problems by killing the Q of the series-resonant circuit.*

determined by the negative supply current of the op amp.

The LM12 is normally stable when it drives resistive, inductive, or small capacitive loads. Large capacitive loads would interact with the open-loop output resistance (about 1Ω), reducing the phase margin of the feedback loop and ultimately causing oscillation. The critical capacitance depends upon the feedback applied around the amplifier: A unity-gain follower can handle about 0.01 µF, while more than 1 µF doesn't cause problems as long as the loop gain doesn't go below 10. If you configure the op amp for loop gains greater than unity, you can enhance the stability of the closed-loop circuit by placing a speed-up capacitor across the feedback resistor.

In all cases, the op amp will behave predictably only if the supplies are properly bypassed, ground loops are controlled, and high-frequency feedback derives directly from the output terminal. Further, so-called capacitive loads are not always purely capacitive. A high-Q capacitor in combination with long leads can present a series-resonant load to the op amp. In practice, this LC load is not usually a problem, but you should keep the possibility in mind.

You can accommodate large capacitive loads (including series-resonant LC loads) by isolating the feedback amplifier from the load as shown in **Fig 3**. The inductor gives low output impedance at low frequencies while providing an isolating impedance at high frequencies. The resistor kills the Q of series-resonant circuits that are formed by capacitive loads. This resistor should be a low-inductance, carbon-composition resistor. The optimum values for the inductor and resistor depend upon the feedback gain and expected nature of the load, but tolerance need not be tight. You can make a 4-µH inductor by winding 14 closely spaced turns of number 18 wire around a 1-in.-diameter form.

You can stabilize the LM12 for all loads by using a large capacitor on the output, as **Fig 4** shows. This compensation gives the lowest possible closed-loop output impedance at high frequencies and the best load-transient response. The method is suitable for use in voltage regulators.

A feedback capacitor, C_1, connects directly to the output pin of the IC. The output capacitor, C_2, is connected at the output terminal with relatively short leads. Use single-point grounding to avoid dc and ac ground loops.

The impedance Z_1 is that of the wire connecting the op amp's output to the load capacitor. About three inches of #18 wire (70 nH) provides stability; an 18-in. length (400 nH) begins to degrade load-transient response. If you use a plastic-film or solid-tantalum capacitor with an equivalent series resistance (ESR) of 0.1Ω, the minimum load capacitance is 47 µF. Aluminum electrolytic capacitors work as well, although you have to increase their capacitance to about 200 µF to bring ESR below 0.1Ω.

Loop stability is not the only gremlin in op amps that drive reactive loads. Time-varying signals can cause the part's power dissipation to increase markedly, particularly when the op amp experiences the combination of capacitive loads and high-frequency excitation.

Input compensation provides stability

If the LM12's high-frequency loop gain is near unity, the op amp is prone to low-amplitude oscillation bursts when it comes out of saturation. The voltage-follower connection is more susceptible than other connections to such oscillation. You can eliminate this glitching—at the expense of small-signal bandwidth—by using input compensation. You can also use input compensation in combination with LR load isolation to improve capacitive-load stability.

Fig 5a shows an example of a voltage follower that uses input compensation. The R_2-C_2 combination across the input works with R_1 to reduce feedback at high frequencies without greatly affecting response below 100 kHz. A lead capacitor, C_1, improves phase margin at the unity-gain crossover frequency. Optimum operation of the circuit requires that the output impedance of the circuitry driving the follower be well below 1 kΩ even at frequencies as high as a few hundred kilohertz.

Fig 5b shows the application of input compensation in an integrator configuration. Both the follower and the integrator can handle 1-µF capacitive loading without LR output isolation.

To make optimum use of the LM12, you should understand the nature of the op amp's temperature-limiting mechanism. The LM12's output transistors can dissipate power until their peak junction temperature reaches 230°C (±15°C). When this temperature is reached, internal limiting circuitry takes over, regulating peak temperature. **Fig 6**, which gives the peak output-current waveform with the output instantaneously short-circuited to ground, shows how the limiting works. Conventional current limiting holds the short-circuit current near 13A for a few hundred microseconds, then temperature limiting takes over as junction temperature tries to rise above 230°C. The response

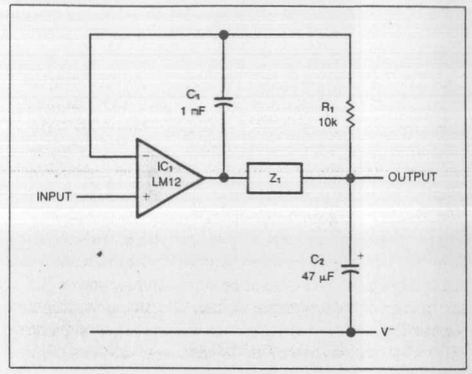

Fig 4—A large output capacitor stabilizes the op amp *for all loads. The impedance Z_1 is that of the wire that connects the IC's output to the load-capacitor terminal.*

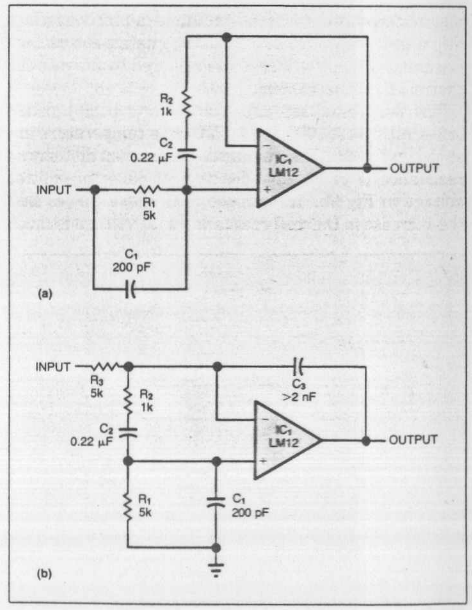

Fig 5—Input compensation reduces bandwidth and increases stability *in low-gain configurations. The method helps stabilize the op amp against capacitive loads for the follower in **a** and for the inverter in **b**.*

Lead inductance and capacitive loading form an insidious alliance that, uncorrected, can cause problems ranging from instability to destruction of the op amp.

time of the temperature limiter is well below 100 μsec.

Because the IC uses this peak-temperature limiting scheme, its power capabilities depend on case temperature, transistor operating voltages, and the way the dissipation varies with time. For two case temperatures, **Fig 7** shows the amplitude of the power pulse required to activate power limiting in 100 msec as a function of collector-emitter voltage on the output transistors. The continuous dissipation limit is about 15% less than the 100-msec limit.

The pulse capabilities of the output transistors are shown in **Fig 8.** The curves give the amplitude of a constant-power pulse required to activate power limiting in the indicated time. When the pulse widths are longer than 1 msec and the collector voltages are above 40V, the pulse capability decreases, as the figure shows.

The guaranteed power ratings of the LM12 are based on a peak junction temperature of 200°C instead of the 230°C limiting temperature. The IC's specs also take test accuracy, guard bands, and unit-to-unit variations into account. The result is that the guaranteed ratings are about 40% lower than those required to activate the thermal-limit mechanism.

The worst-case, safe-area curves for a peak junction temperature of 200°C and a 25°C case temperature are shown in **Fig 9a.** The guaranteed-maximum dc thermal resistance is given as a function of collector-emitter voltage in **Fig 9b.** You can see from these curves that the increase in thermal resistance with voltage is much smaller at higher case temperatures. Finally, **Fig 9c** shows the equivalent thermal resistance for power pulses. Again, these are worst-case numbers. The voltage dependency of thermal resistance in **Fig 9c** is for a 25°C case temperature. At higher case temperatures, this dependency is more moderate (**Fig 9b**).

Under the condition of ac loading, both power transistors share the dissipation, and the worst-case thermal resistance can drop to 1.9°C/W. However, the frequency of the signal must be high enough that the junction temperature doesn't exceed the peak ratings of either output transistor.

Derate the maximum junction temperature

It's not unusual for designers to derate the maximum junction temperature of semiconductors below the manufacturer's specified value. In general, the junction-temperature limit for power semiconductors is 200°C, although standard junction-temperature limits for hermetic or plastic packages might differ.

The LM12 can operate continuously at 200°C. Such conditions as out-of-spec line voltage or lack of air circulation would cause the equipment to stop working temporarily; the part would not suffer excessive stress or catastrophic failure. In certain applications, however, a temporary shutdown can have the same effect as a permanent one; you should definitely use derating in such applications.

Modern IC power transistors don't experience catastrophic failure over a short term, even when peak

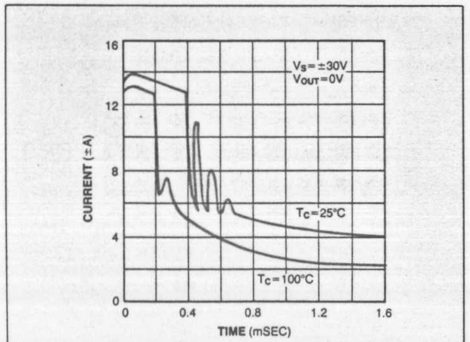

Fig 6—Internal limiting circuitry regulates peak temperatures in the LM12. The circuit reduces output short-circuit current when the transistors' junction temperature reaches 230°C.

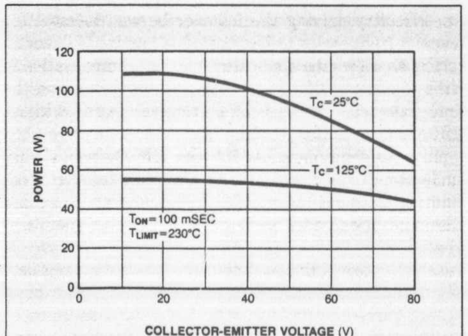

Fig 7—The power required to activate the power-limit mode in the LM12 is lower for higher collector-emitter voltages, but the drop-off diminishes for very high case temperatures.

A power IC's thermal aspects

In a power IC, the peak junction temperature occurs at the center of the power transistor. At the edge of the power transistor, the temperature rise (junction-to-case) is only 60% of that at the center. **Fig A** shows the surface-temperature profile, moving out from the center of the power transistor, for a situation in which the peak junction temperature is 200°C and the case temperature is 75°C. In this idealized 2-dimensional plot, the temperature at the edge of the power array is only 160°C.

In real situations, the temperature falloff can be considerably greater than that indicated by the curve. Earlier IC designs have located the sensor several mils away from the power array. As a result, the temperature sensor responds to about 30% of the temperature rise in conventional power-IC designs.

Truly effective temperature sensing requires a sensor that is distributed throughout the power array, yet responds to the peak temperature almost instantaneously. In the LM12 design, these requirements are met by a thermal-sense emitter, located a fraction of a mil from the active emitter, that winds through the entire power array.

In ICs using conventional thermal limiting, the output transistors' junction temperature is controlled at lower case temperatures via foldback current limiting, which restricts power dissipation. When case temperature rises to a certain level, the thermal-limiting mechanism is activated. In general, the peak limiting temperature will be substantially greater than the thermal limit, because the sensor doesn't respond to the full temperature rise.

Fig B is an idealized plot of peak junction temperature for increasing case temperature. The plot is drawn with the assumption that the thermal limit is 150°C, rise in power-limit mode is 150°C, and the thermal sensor responds to one-third the peak temperature. These operating conditions are typical for many IC designs.

Because of the tolerances involved in a practical foldback-current-limit design, worst-case dissipation in such a design can be twice the typical values. Further, such designs are subject to non-ideal 3-dimensional effects. Peak junction temperatures well above 300°C can occur in ICs that use conventional limiting techniques. Peak-temperature sensing, however, makes foldback current limiting unnecessary: The power transistor can handle full rated voltage and current simultaneously, yet be fully protected.

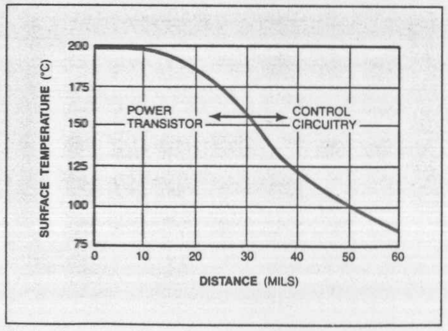

Fig A—In a power IC, peak temperature occurs at the center of the power transistor. The IC's surface temperature drops, going from the center of the power transistor out into the control circuitry. The active emitters at the edge of the power array are at x=0.

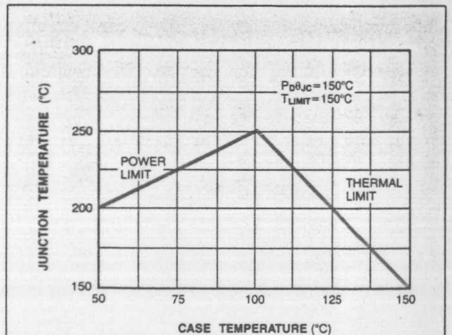

Fig B—In many ICs, maximum thermal stress doesn't occur in the absence of a heat sink, as this plot indicates.

To determine the heat sinking needed for a power op amp, you must understand the temperature profiles on the surface of the op amp's die.

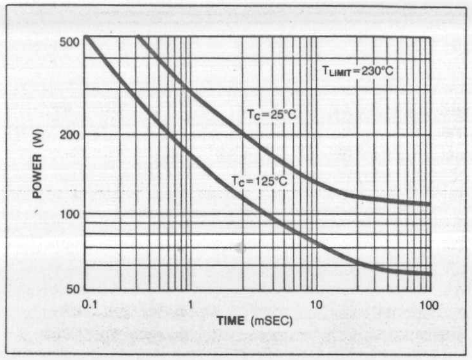

Fig 8—The peak-dissipation capability of the LM12 depends on pulse duration. For pulses wider than 100 msec, the external heat sink determines the ratings.

junction temperatures reach 300°C. However, power cycling can cause problems. For example, in power transistors having a soft-solder die-attach, die-attach failures can take place after 30,000 cycles and a 70°C temperature rise. The LM12 avoids such failures by using a gold-eutectic die-attach and a molybdenum spacer. Even so, when dissipating 200W, the LM12 has exhibited metallization failures after one million cycles from 50°C to power limit at 230°C.

Thermal derating is more important for the op amp's control circuitry than for its power transistors. Operating the control circuitry at temperatures above 150°C can affect reliability. Fortunately, the control circuitry is exposed to only a fraction of the temperature rise in the power transistors. You can base derating on a thermal resistance of 0.9°C/W, independent of operating voltage. With ac loading, where power dissipation occurs in both power transistors, this thermal resistance drops, finally approaching 0.6°C/W.

The LM12's ratings are based on the case temperature as measured on the bottom of the TO-3 package near the center. To minimize the thermal resistance between this region and the heat sink, you must be sure to mount the IC correctly. For example, when mounting the package directly to the heat sink, you should use a good thermal compound such as Wakefield Type 120 or Thermalloy Thermacote. Without this compound, thermal resistance will be no lower then 0.5°C/W, and it may be much worse. With the compound, thermal resistance will be 0.2°C/W or less, assuming that the package and the heat sink have <0.005-in. combined

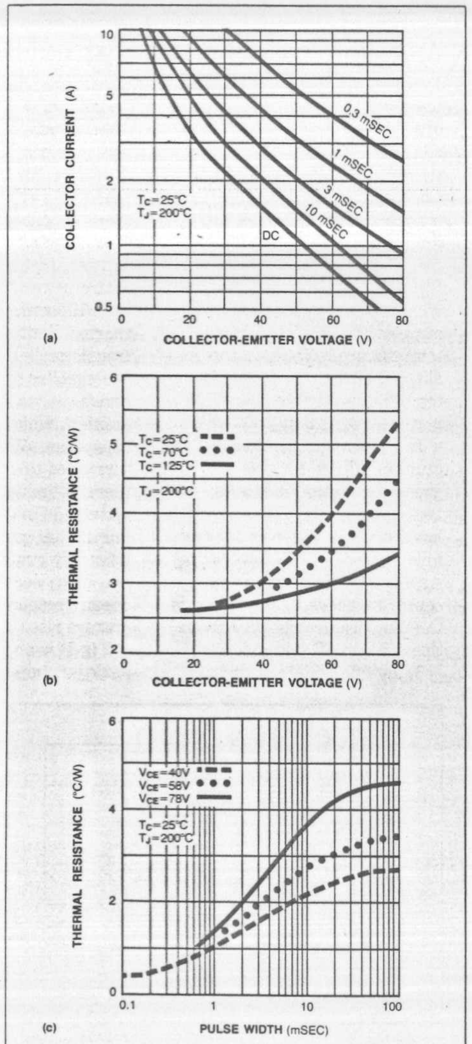

Fig 9—Three thermal curves characterize the LM12's power ratings. The curves are the safe-area plot (a), the change in dc thermal resistance with temperature and operating voltage (b), and the pulse thermal resistance (c).

When you use a heat sink with a high-power amplifier, you must take care to minimize the thermal resistance between the amplifier's case and the heat sink.

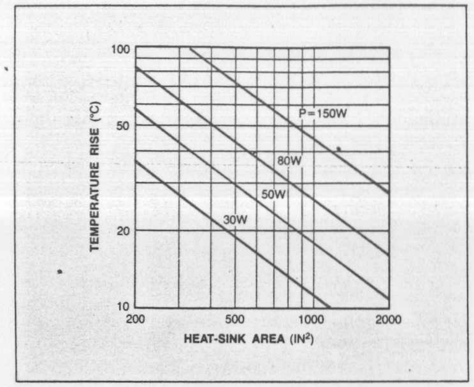

Fig 10—You need a heat sink to cool the LM12's package. These curves give the rise in case temperature as a function of heat-sink fin area; the curves assume that the part uses convection cooling.

flatness run-out. Proper torquing of the mounting bolts is also important: You should use four to six inch-pounds of torque.

If you must isolate V^- from the heat sink, you must use an insulating washer. If you use hard washers made of beryllium oxide, anodized aluminum, or mica, you must use thermal compound on both faces. Two-mil mica washers are the most common; they yield about 0.4°C/W interface resistance when you use them with the compound. Silicone-rubber washers are also available. Some vendors claim their rubber washers offer 0.5°C/W thermal resistance without thermal compound. Note, however, that these rubber washers deteriorate; you must replace them if you remove the IC.

Choose the right heat sink

You'll need to attach a heat sink to the LM12, because without one, the op amp (with ±40V supplies and no load) can experience an internal temperature rise as high as 160°C. The types most suitable for dissipation of about 50W are made from an extruded aluminum channel equipped with multiple fins. It's important for you to choose a heat sink that has enough metal under the package to conduct heat from the center of the package bottom to the fins without introducing excessive temperature drop.

The power rating of a multifinned heat sink is determined largely by the surface area that's subject to convection cooling and by the allowable temperature rise to ambient. Heat loss from radiation can also be an important factor in simple heat sinks. However, for a heat sink in which multiple fins radiate toward each other, the radiation term is insignificant. Nevertheless, heat sinks are usually black anodized to maximize radiated heat.

Fig 10 lets you estimate fairly accurately the surface area required for a given temperature rise and power dissipation. The heat sink's orientation, length, and fin spacing affect the area efficiency. The curves are drawn with the assumption that the surfaces are located in a vertical plane. If the surfaces are horizontal, the temperature rise increases by, say, 20%. Vertical dimensions longer than 4 in. are less efficient. Commercial heat sinks are normally designed so that fin spacing is not close enough to affect the performance shown in **Fig 10.**

It's not possible to specify an unqualified thermal resistance for a convection- or radiation-cooled heat sink. Both mechanisms will give a lower thermal resistance when temperature rise increases, and heat losses from radiation also increase as absolute temperature increases. Because radiation losses are not dominant in multifinned heat sinks, power dissipation and temperature rise characterize performance. You can drastically reduce heat-sink size by using forced-air cooling. **EDN**

Authors' biographies

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Article Interest Quotient (Circle One)
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